Production of the exotic Θ baryon in relativistic nuclear collisions

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Motivated by the recent apparent experimental confirmation of the predicted exotic baryon $\Theta(1540)$, we have discussed its relevance to high-energy nuclear collisions [1]. Obviously, if this particle indeed exists, it would enrich the hadronic dynamics and ought to be included in models treating the hadronic resonance stage of the collisions.

Using an extended chiral soliton model, Diakonov *et al.* [2] have made quantitative predictions for a previously conjectured exotic anti-decuplet of baryons. The Θ is the lightest of these and would be the most easily identifiable. It can be considered as a $uudd\bar{s}$ pentaquark resonance state having spin $J=\frac{1}{2}$, isospin $I=0$, and strangeness $S=+1$ (hence a charge of $Q=+1$) and it has been named the Θ baryon. Its mass was prediced to be about 1530 MeV and its decay width less than 15 MeV. The dominant decay modes are $\Theta \to K^+n$ and $\Theta \to K^0 p$. Various recent experimental data appear to confirm the existence of this exotic baryon.

In view of the mutually consistent experimental evidence for the existence of the Θ, it is reasonable to consider the implications for high-energy nuclear collisions where baryonic resonances are abundantly produced. Since it carries a unique combination of baryon number, charge, and strangeness the Θ may provide a valuable additional diagnostic tool. Especially useful may be the fact that it is a $S=+1$ baryon, which could help improve our understanding of strangeness production.

In order to provide a rough estimate of the expected yield, we have invoked the framework of statistical equilibrium, which has been found to account very well for the observed hadronic abundancies over a wide range. In a grand-canonical ensemble of hadron species i, the partition function factorizes into separate contributions for each specie, $Z=\Pi_i Z_i$, with

$$\ln Z_i(T,V,\{\mu\}) = \pm \frac{VTg_i}{2\pi^2} \sum_{n=1}^{\infty} \frac{(\pm\lambda_i)^n}{n^2} m_i^2 K_2(\frac{nm_i}{T}) \ , \qquad (1)$$

where plus is for bosons and minus is for fermions. The hadron mass is m_i and g_i=2J_i+1 is the spin degeneracy. The fugacity associated with the hadron specie i is

$$\lambda_i(T,\{\mu\}) = \mathrm{e}^{(B_i\mu_B+Q_i\mu_Q+S_i\mu_S)/T} \ , \qquad (2)$$

where B_i, Q_i, and S_i denote baryon number, electric charge, and strangeness, respectively. The ensemble is characterized by the temperature T and the three chemical potentials $\{\mu\}=\{\mu_B,\mu_Q,\mu_S\}$. Finally, V is the enclosing volume of the system.

These simple estimates suggest that the Θ may be produced at a level of approximately 6% relative to the proton yield and about 14% of the Λ yield, rather independently of the prevailing chemical potentials (as long as their values are reasonably consistent with the observed yield ratios).

Further insensitivity to the somewhat poorly understood strangeness suppression effect can be obtained by taking double yield ratios designed to ensure counterbalancing of the various conserved attributes (baryon number, charge, and strangeness). By this method, using the observed π^+, K^+, and p multiplicities, we estimate that about one Θ per unit rapidity will be produced at mid rapidty in central Au+Au collisions at 100 GeV/A.

Since the expected Θ yield is thus not negligible, we have encouraged that the data be analyzed for the purpose of establishing Θ production in heavy-ion collisions. This task could be carried out by examining the invariant mass spectrum for the pK_s^0 system, with the K_s^0 being measured by means of its $\pi^-\pi^+$ decay vertex. In view of the possible existence of an entire Θ multiplet, it might be worthwhile to examine also the pK^+ invariant-mass spectrum at the same time.

One possible method of analysis for identifying the Θ might be to consider the invariant-mass spectrum of the $K_s^0 p$ system. In addition to the readily available kinematic information on the proton, this approach requires the K_s^0 mesons to be identified through their $\pi^-\pi^+$ decay vertex. This should be possible as well with the existing instrumentation (using the STAR TPC, for example). Presumably, since the intrinsic Θ decay width is so small, the observed width would primarily reflect the detector resolution (the construction of the $p\pi^-\pi^+$ invariant-mass spectrum requires complete kinematical information for all three final hadrons). To the degree that the associated instrumental tolerances are well understood, it should then be possible to predict the observable width, thus facilitating the identification of the signal.

The Θ may also be of interest on the theoretical side since microscopic transport models usually attempt to include all known hadronic resonances. In these treatments, a primordial hadronic population generated by model-specific mechanisms undergoes further evolution involving both decays and reactions. As a result, both the thermodynamic properties of the hadronic resonance gas (such as pressure and entropy) as well as the final yield of the detectable hadron species are affected by the selection of included resonances.

Thus, insofar as the existence of the Θ baryon resonance can be considered established, it would seem natural that it be included in those treatments. While its expected relatively small abundance will likely render it ineffective with regard to modifying the overall thermodynamic conditions, it may play a role for the abundance of other relatively rare species. In particular, it might be of interest to investigate how strangeness-related quantities might be affected by the presence of the Θ.

[1] Jørgen Randrup, Phys. Rev. C **68**, 031903(R) (2003).
[2] D. Diakonov, V. Petrov, M. Polyakov, Z. Phys. **359**, 305 (1997).